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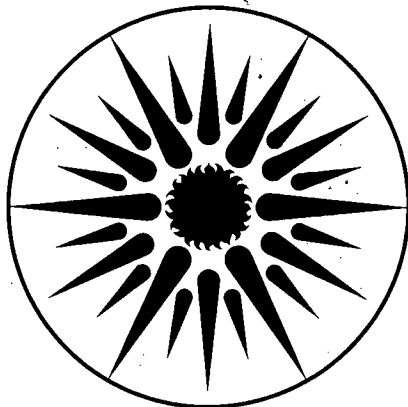
A COMPREHENSIVE APPROACH TO THE INTEGRATION OF  
DAYLIGHT AND ELECTRIC LIGHT IN BUILDINGS

E. Ne'eman

August 1983

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A COMPREHENSIVE APPROACH TO THE INTEGRATION OF  
DAYLIGHT AND ELECTRIC LIGHT IN BUILDINGS

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A Comprehensive Approach to the Integration of Daylight  
and Electric Light in Buildings

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Abstract

Effective daylighting within an interior space depends to a large extent on the shape and size of the building. However, it is often impossible to illuminate a building exclusively by daylight. In this paper an attempt is made to sum up the past and present attitudes regarding optimal utilization of daylight in deep interiors. Such an optimal solution seems to be an integration of daylight and electric light.

Various concepts of integration are examined, starting with PSALI, and a comprehensive list of types of integration is proposed. The preferred type for a specific design depends on activity pattern, visual requirements, location, climate, etc. Human requirements, energy saving, and cost-effectiveness are examined to propose strategies for optimal integration.

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## Introduction

Integration of daylight and electric (artificial) light in buildings during daytime hours can be described as a holistic design process for the visual environment. In this process the merits and deficiencies of both daylight and electric light are considered in order to arrive at the optimal design for a specific project. This optimal solution depends on the type of building, activity patterns in it, and local environmental factors. Simultaneous utilization of daylight and electric light during daytime, if not closely coordinated during the design process, seldom achieves optimal results.

Hopkinson developed the first concept of integration, known as Permanent Supplementary Artificial Lighting of Interiors (PSALI) [1,2]. Recommendations based on PSALI were later made by the British Illuminating Engineering Society [3].

The original PSALI concept of the late forties was based on conditions that no longer exist. At that time the recommended illuminance for school classrooms was 15 lm/ft<sup>2</sup> (15 fc or about 160 lux) and for offices 20 lm/ft<sup>2</sup> (20 fc or about 215 lux). It was clear that in deep interiors, the available levels of daylight caused the harsh contrast between interior background surfaces and the bright sky visible through the windows, thus affecting the adaptation of the eye. On the one hand, the back of the room would look too gloomy while, on the other hand, the windows would appear too bright.

The simplest way to counteract the gloom and reduce contrasts was to switch on the electric lighting. However, the established levels of that time (160-215 lux) proved inadequate, so higher levels were recommended for daytime electric lighting at the depth of the room than were recommended for nighttime hours (see Figure 1). Furthermore, the higher the daylight level in the room, the higher the electric illuminance had to be.

One of the basic requirements of PSALI was that daylight should be the major light source, which would be supplemented by electric light in the deeper parts of the interior and should have spectral properties as similar as possible to daylight. Less clearly defined in the original PSALI concept were the directional requirements of the integrated light.

Since then recommended illuminance levels have increased, and deeper and larger buildings have been built, requiring extension of the integration concept. Ne'eman [4] and later Ne'eman and Longmore [5] and others, suggested that the scope of integration should be widened to include various types of buildings, and PSALI should become one of several types of integration. In a paper entitled "The Successor to PSALI" [6], Collins suggested that IDAL--Integration of Daylight and Artificial Light--should succeed PSALI.

The present paper surveys the development of concepts of integrating daylight and electric light in view of modern trends in architecture and the growing awareness of energy conservation.

Artificial Light--should succeed PSALI.

The present paper surveys the development of concepts of integrating daylight and electric light in view of modern trends in architecture and the growing awareness of energy conservation.

Proper understanding of the integration process is of utmost importance for planners in countries where the design of the visual environment has involved extremes. Windowless buildings with no access to daylight or view on the one hand, and overglazed buildings with tremendous energy and glare problems on the other, have been common design fashions for more than half a century.

### Design Objectives

The design objectives of the early integration method (PSALI), were intended mainly to improve the visual environment by adding electric light to available daylight. Later on the importance of the view through windows was recognized as an inseparable part of an integrated design. The window came to be considered not solely as a source of natural light, but also as a means of visual communication through which valuable information is obtained. As a result, the evolution of the integration concept has reduced reliance on the dominance of daylight.

The design objectives have been transformed into the provision of task, or functional, illuminances by electric sources, while daylight is assumed to meet the subjective requirements for a view and contact with the outside. These requirements influence acceptable window size, as will be discussed in detail later.

Energy considerations were not ignored by the early integration methods. However, the crucial importance of energy savings and cost-effectiveness became a major feature in daylight integration during the seventies, due to the energy crisis.

The motto of integration at present should be: utilize daylight to the maximum possible extent, and use electric light minimally. However, human performance and well-being should not be sacrificed. It is worth noting that well-being, energy savings, and lowest overall cost do not necessarily achieve their optimums simultaneously. In any case, we believe that basic human needs should be met.

The dilemma between maximum energy savings and optimal overall costs is a serious one in daylight design. Oversized windows in some cases can minimize the use of electricity for lighting. Because of reduced thermal insulation, however, the overall costs of building management may be higher than with a solution based on an integrated scheme. In our opinion the design objectives should seek a solution in which minimal overall costs are obtained with the greatest possible energy savings, visual performance, and visual well-being. The logic behind this preference in design objectives is that buildings are built to last a long time, while energy costs are unpredictable and may fluctuate over time.

Current design objectives can be divided into the following major categories:

1. Human performance and well-being

This category primarily concerns the visual environment, including visual performance and visual well-being. Thermal and acoustical comfort should not be overlooked, however.

The quality of the visual environment depends generally on adequate illuminance for visual activity, limitation of glare, and subjective considerations such as avoiding a gloomy interior, achieving a color scheme, and providing an acceptable size and shape of windows to maintain contact with the outside world. Daylight admitted through windows is also considered essential for photobiological processes, such as controlling the biorhythms in the body and stimulating metabolic functions.

2. Effective energy management

The total energy balance should be examined in light of optimal energy efficiency. Regarding daylight admission, the energy balance of heat gains and losses due to solar radiation, conduction, and air leaks should be evaluated. For electric light, the overall system efficacy, not only lamp efficacy, should be taken into consideration.

3. Cost-effectiveness

The overall cost mentioned above should include depreciation and interest on the investment as well as the operating costs for fenestration, shading, and the electric lighting system.

4. Dynamic controls

We can state as a rule that almost any fixed or static shading system is inevitably energy-inefficient. For example, fixed shading devices will unnecessarily reduce the amount of daylight indoors even when the sun is not shining on them. As a result, more electric light will have to be used than with adjustable or operable shades. Similarly, most large electric light systems that are controlled by a single master switch will tend to use more energy than justified by functional needs. Again, the more controllable the system is, the higher the energy-saving potential.

The highest degree of flexibility is obtained by an integrated control system that simultaneously monitors the electric lighting and shading systems for maximum utilization of daylight and minimum consumption of electric lighting.

The Window in the Integrated System

The role of windows was mentioned earlier. In addition to admitting light and providing ventilation in non-air-conditioned buildings, windows have a subjective psychological role, providing visual contact with the outside, as described by Marcus [7], Ne'eman and Hopkinson [8], Keighley [9], and Seidl [10].

In their study on the critical minimum acceptable window size, Ne'eman and Hopkinson [8] suggested that satisfaction with a window depends on the information conveyed by the view. It was shown that in work interiors satisfaction with window width increases until the window reaches about 30% of the window wall width, provided the window is located within a horizontal angle of about  $60^{\circ}$ . This angle should be measured from workplaces whose occupants have visual contact with the windows (see Figure 2).

It was also shown that whenever the view provides little information, such as a view of the sky through high-up vertical windows or through rooflights (skylights), the windows are perceived as merely sources of daylight and have little psychological-subjective significance as sources of meaningful visual contact and relief from a sense of enclosure. It is interesting to note that satisfaction with a space that has windows does not necessarily imply that the view out will be available to every occupant in every place or work station. Most people are satisfied if they know they have the option of looking out if they wish to, by turning their heads or by standing up from their sedentary working positions.

The choice of sill and window height is also related to the view content. The lower part of the window provides more information than the upper part. Thus relatively wide and lower windows are more satisfactory from a subjective point of view. However, higher windows are more efficient in admitting sky light to the deeper parts of the interior. We see that by specifying the glazed area of fenestration, we do not necessarily meet the well-being requirements for the minimal window opening. Thus, it is recommended that the suggested above minimum width of the window(s) be applied to any size and shape of openings on vertical walls.

A simple way of specifying window size and area is recommended as a standard in Germany--see Seidl [10] and Krochmann [11]. It is suggested there that a daylight factor of 0.9% at half the depth of a room, near the side wall, can provide sufficient brightness in winter for at least two hours at noontime. In addition, a minimum window area of 30% of the window wall is required for subjective well-being, and a window height of 1.2 m is considered optimal.

It should be stressed that overglazing, in fully glazed exterior walls, does not bring any subjective advantage, in addition to creating thermal deficiencies and glare problems. In some cases such a solution may lead occupants to complain of lack of privacy and personal security.

In our opinion, the final choice of window area should be left to the designer. For working interiors, the minimum width should always be provided. Beyond that, the size of the glazed area should be dictated by the design objectives that are discussed above. In dwellings even more emphasis should be given to subjective-psychological considerations.



## Depth of Daylight Penetration and Relationship to Electric Light

It is well known that in interiors where daylight comes through the windows on one wall, illuminance near the windows is relatively high. It falls very rapidly the farther we move from the windows. The actual illuminance depends on the available daylight outdoors, external obstructions, glazing transmittance, and interior geometry and internal reflectances. The depth to which daylight can provide the required illuminance also depends on the activity pattern. An interesting investigation was carried out by Matsuura [12] on the "Turning-off Line in Perimeter Areas for Saving Lighting Energy in Side-Lit Offices." In this paper he suggested dividing the electric lighting installation into two parts. The lighting at the depth of the room does not interact with daylight and remains on throughout the working day. The perimeter area lighting can be switched off during daytime hours if conditions allows. The depth of this perimeter zone can be determined with the aid of nomograms proposed by the author.

Switching off the lighting in the area close to windows can be performed by the simplest manual on-off operation. More recently, other solutions have been introduced. On-off switching of groups of luminaires can be connected to photoelectric sensors that automatically control the switching according to the distance from windows. The most sophisticated system involves the automatic dimming of the electric lighting in all the parts of a building that can utilize daylight.

Obviously, the more sophisticated the lighting system, the more expensive it becomes. So, as mentioned before, the economical feasibility and pay-back time should be examined in addition to energy savings. In many cases the simpler solution of automatic on-off switching may prove to be optimal.

It is worth mentioning that for maximum energy savings the most efficient lamps and ballasts should be used, and regular cleaning, maintenance, and relamping should be carried out at predetermined intervals.

## Daylight Glare

Visual comfort is one of the most important criteria in lighting design; however, it cannot be achieved in the presence of glare. Light sources of any kind naturally present the brightest surface to the field of view, where they create the most intense glare. Generally speaking, the degree of glare depends on the luminance of the source and its background and on the size of the source and its location in relation to the direction of view.

The sources of daylight glare are direct sunlight and bright sky as seen through daylight-admitting openings. Direct sunlight must always be controlled to avoid intolerable glare. On bright days the sky may cause quite severe discomfort glare. In particular, if light is admitted through windows that are located at eye level, these windows are likely to be in the occupants' primary lines of vision. Furthermore, windows are larger than luminaires so that the distinction between the

glare source and its background as perceived by the retina of the eye is not clearly definable. As a result, daylight glare cannot be evaluated by the same calculation procedures used for glare from electric luminaires.

In a recent paper on the state of the art in daylight glare, Collins et al. [13] indicated that laboratory experiments have shown reasonable correlation with predictions by the Hopkinson-Cornell large-source glare formula. They also show that if the window area is greater than about 2% of the floor area of the room, the size of windows has relatively little effect on the glare perceived by a person looking directly at the window.

The authors recommend that designers provide means to reduce the discomfort glare from daylight by properly locating work stations so that occupants' main views do not include the sky or other external bright surfaces, and to reduce window luminance by using suitable shading devices. They also recommend light-colored surfaces around windows.

The addition of electric light away from the windows merely to reduce contrasts, and thus reduce discomfort glare, is not recommended because of energy considerations. However, in integrated systems, electric light is needed anyway. So if it is properly designed, it can become a successful means of controlling daylight glare.

Summing up, an integrated design involving daylight admission, controllable shading devices, and proper use of electric light can most effectively limit discomfort glare and keep it below annoyance levels.

### Spectral Characteristics

Daylight is continuously variable in intensity, direction, and spectral characteristics. In special cases where the visual task involves accurate color judgments, reference should be made to the particular spectral distributions concerned--see Henderson and Hodgkiss [14] and [2].

Electric light sources have fixed spectral distributions that can be defined precisely (see Figure 3). Data can be obtained from manufacturers' literature and guides on lighting such as Refs. [15] and [16].

For most work activities, however, there are no strict demands for accurate color discrimination, and a wide range of lamps can be selected for integrating with daylight according to criteria that relate to the qualitative aspects of the total visual environment. Nevertheless, the electric lighting should have a color appearance and color-rendering characteristics compatible with those of the daylight. It should also be compatible with interior color finishes.

Effective integration calls for lamps that make the occupants unaware, or at least unconcerned, that part of the interior is lit by daylight and the remainder by electric light.

The efficient types of fluorescent lamps are the favorite sources for general-purpose integration. For accurate color judgment, the less efficient "de-Luxe" types, having superior color-rendering properties, should be used. The new generation of so-called "Tri-phosphor" lamps, which are more efficient than the de-Luxe lamps, should be used with caution. The reason is that, in spite of their fairly high overall color-rendering, significant distortion may occur at some specific wavelengths.

### The Direction of the Flow of Light

The directional properties of daylight, which comes in the majority of cases through vertical side windows, differ from those of the general electric lighting, which usually comes from above. However, it should be borne in mind that the resultant flow of light from either diffused daylight or electric light is not highly directional inside interiors having interreflections from all surfaces. The exception is direct sunlight, which is generally limited in its penetration or excluded altogether.

The importance of the directional properties of lighting in a working space depends greatly on the activity pattern. Just as people usually pay little attention to the spectral properties of integrated lighting, in most cases they tend to ignore the differences in the directions from which light reaches their working surfaces. This does not mean that directional characteristics are unimportant, but that they are satisfactory for the majority of visual activities. However, in some visual tasks, such as detection of fine details in texture or enhancement of form and shape, directional properties can markedly influence visibility.

The concept of modeling was suggested by Lynes et al. [17,18] as a way to describe the directional characteristics of light. Ne'eman and Longmore [5] have proposed an Integration Factor as a quantitative measure for the integration of daylight and electric light. This factor is defined by using the vectorial representation of the light field--see Gershun [19] and Helwig and Krochmann [20]. However, we believe that more work should be done to quantify the directional properties of the light flux in integrated systems.

### Integration, Climate, and Energy

The preferred type of integration is naturally related to local factors such as climate, daylight availability, cost of electric power, peak demand, etc. In predominantly cold climates, emphasis on the use of electric lighting may be justified because the lighting power contributes to the heating requirements, and thus is not lost and does not have to be removed. Also, in cold climates daylight tends to be less available on an annual basis than in warmer regions.

On the other hand, in predominantly hot climates daylight should be utilized as long as possible because of its abundance and higher luminous efficacy (100-120 lm/W), compared with electric light sources of

similar spectral distribution (40-70 lm/W, including ballast losses).

We see that lighting power consumption is an integral part of the overall energy management of a building. It should be mentioned that from energy considerations alone, the more efficient the electric lighting becomes, the less advantageous is the utilization of daylight. As mentioned before, however, there are other considerations that make daylight the preferred source for interior lighting. Furthermore, the integration of daylight and electric light can utilize both sources optimally.

### Methods of Integration

Because it was recognized that a single integration technique cannot cover all types of buildings and activities, attempts have been made to find a comprehensive classification of integration methods.

A draft report on the integration of artificial light with daylight, submitted by Longmore [21] to the CIE Daylighting Committee TC-4.2, suggested classifying the design guidelines for integration according to building type. Consequently, a wide range of buildings has been selected: offices, offices where machines are used, computer rooms, drafting rooms, industrial buildings, hospital wards, libraries, and commercial kitchens and laundries. Long as it is, such a list cannot cover all building types.

Another approach has been adopted in Germany [11], where buildings are classified as residential or non-residential for purposes of integration design.

A more comprehensive approach seems to be a classification of integration methods, rather than building types [4,5]. Then every building can be designed using the appropriate integration method, which can also take into account specific local requirements and constraints. The proposed methods of integration are:

1. Single (mono) space integration with daylight dominant:
  - 1a. with daylight entering through windows on vertical walls (see Figure 4);
  - 1b. with daylight entering through rooflights (skylights) (see Figure 5).
2. Single (mono) space integration with electric light dominant:
  - 2a. as 1a above (see Figure 6);
  - 2b. as 1b above.
3. Interspace integration--in a building using daylight in peripheral rooms and electric light in inner rooms (see Figure 7).
4. Transitional integration--the coordination of adaptation levels in areas where people enter or leave a windowless building.
5. Outdoor Integration---for outdoor activities extending from daylight into dark hours. There is no change in location or space, but a

time-dependent transition into which the lighting should be integrated throughout the activity.

The major characteristics of these integration methods are listed in Table 1.

#### Dynamic Integration of Daylight and Electric Light--DIDEL

We now add a new dimension to the known integration techniques--dynamic controls. The ultimate control system should include all environmental factors, i.e., thermal, visual, and, to some extent, acoustical. However, at this stage we are concerned primarily with the visual environment where electric lighting and shading devices are involved.

Manual switching of sections of the electric lighting system already provides a kind of dynamic option. Regretfully, it is only too well known that manual lighting controls have not been widely used. For this reason a dynamic integration can be achieved only with automatic controls.

We can currently use high-technology automatic devices, which provide us with a wide variety of control options. A few examples are studies by many research centers, such as work by Crisp [22], at the Building Research Establishment in England, by Selkowitz [23], Rubinstein [24], and others at the Lawrence Berkeley Laboratory in the USA.

Strangely enough, we currently have much knowledge on the technical aspects of lighting controls, while the human acceptance of such controls has not been investigated thoroughly enough. Occupant response to high-technology control is now being studied at the Lawrence Berkeley Laboratory by Ne'eman and Sweitzer [25].

In conclusion, we suggest that DIDEL should aim at the maximum utilization of daylight and the minimum possible use of electric light to create an efficient and pleasant visual environment. Lighting energy consumption should be analyzed as part of the total energy use of the building. In our opinion, as stated before, the proper design strategy is overall minimum cost of the lighting environment and not maximum energy saving.

Special care should be given to visual well-being by providing an acceptable view through windows and by avoiding excess glare from windows and luminaires.

#### ACKNOWLEDGEMENT

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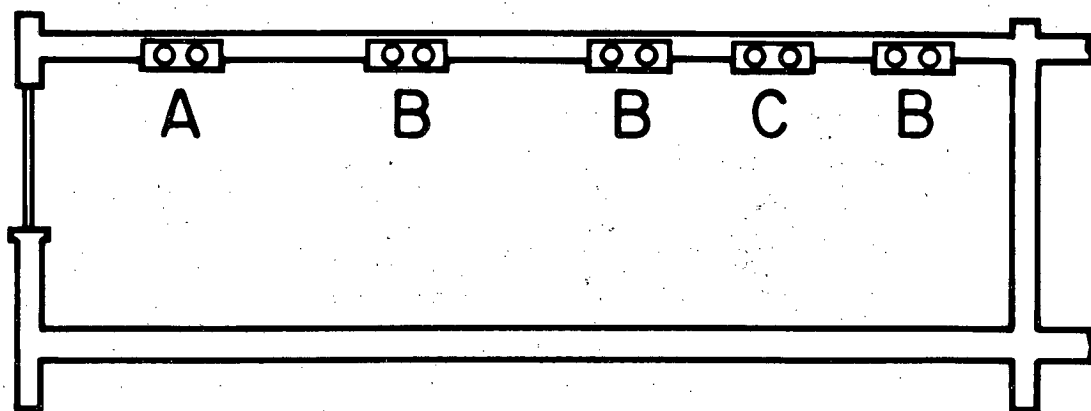
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Table 1. METHODS OF INTEGRATION OF DAYLIGHT WITH ELECTRICAL LIGHT

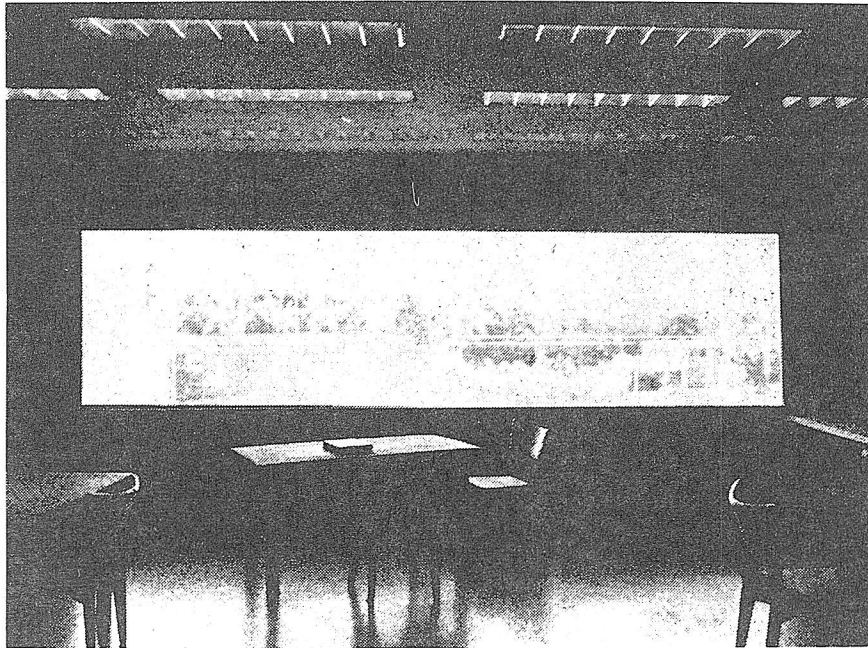
NUMBER	1a	1b	2a	2b	3	4	5
SPACE INTER-RELATIONSHIP	Single (mono) Space Integration				Interspace-Spatial Transition Buildings with daylighted peripheral rooms & windowless inner rooms	Entry to and exit from a windowless building	Outdoor activity-temporal transition
DOMINANT LIGHT SOURCE	Daylight (PSALI)		Electric Light		Daylight in peripheral rooms; electric light in inner rooms	Daylight outdoors; electric light indoors	Daylight during light hours; electric light during dark hours
HOW DAYLIGHT IS ADMITTED	Vertical outer walls	Rooflights: possible only on top floors	Vertical outer walls	Rooflights: possible only on top floors	Vertical outer walls	Indoors: windowless; outdoors: full daylight	
ROLE OF DAYLIGHT	Dominant source: for at least part of the space. Allows view and contact with the outside	For the whole space. Limited contact with the outside	To add quality to the lighting and allow a view and contact with the outside	Background lighting and as a supplement to electric light	Dominant source in peripheral room; little deeper penetration	Graduation of intensities according to fluctuations of daylight	Exclusive source during light hours; mixed with electric light during semi-dark periods
SIZE OF OPENINGS	Large windows exceeding minimum acceptable size	Large rooflights to illuminate the entire space	Smaller windows- however, not smaller than the minimum acceptable size	Smaller rooflights to admit a noticeable amount of daylight	For peripheral rooms as 1a; no windows in inner rooms		
ROLE OF ELECTRIC LIGHT	Zonal supplement to poorly daylighted areas; local lighting	Uniform supplement to daylight throughout the space on cloudy dull days; local lighting	Functional (task) lighting  General lighting		Exclusive source in inner rooms	Exclusive source in windowless buildings	Exclusive source during dark hours
SIMILARITY OF SPECTRAL PROPERTIES OF ELECTRIC SOURCES TO DAYLIGHT	Important  Critical for accurate color judgments		Important  Any good color-rendering source can be used for accurate color judgments		As 1a	As 2a	Prime importance for TV coverage
DIRECTIONAL PROPERTIES: DAYLIGHT	Side	Above	Side	Above	side for peripheral rooms		
ELECTRIC LIGHT	Above	Above	Above	Above	Above for all rooms	Above	
EXAMPLES OF SUITABLE USE	Schools; small offices and workshops	Factories; museums	Large land-scaped (open-space) offices, large factories, public buildings, operating theatres	Small or large factories, public buildings	Deep-plan hospitals, offices, public buildings	Large factories, underground structures	Sports stadia, swimming pools
BENEFITS	Visual comfort, optimal energy savings; subjective well-being		Reduced thermal exchange with the outside in cold regions and less exposure to outside noise; in many cases optimal economical solution		Improved visual comfort, particularly for occupants who frequently move from one area to the other	Elimination of "visual shock" on entering or leaving the building	Uninterrupted visual conditions on field and TV screens with transition from daylight to electric light





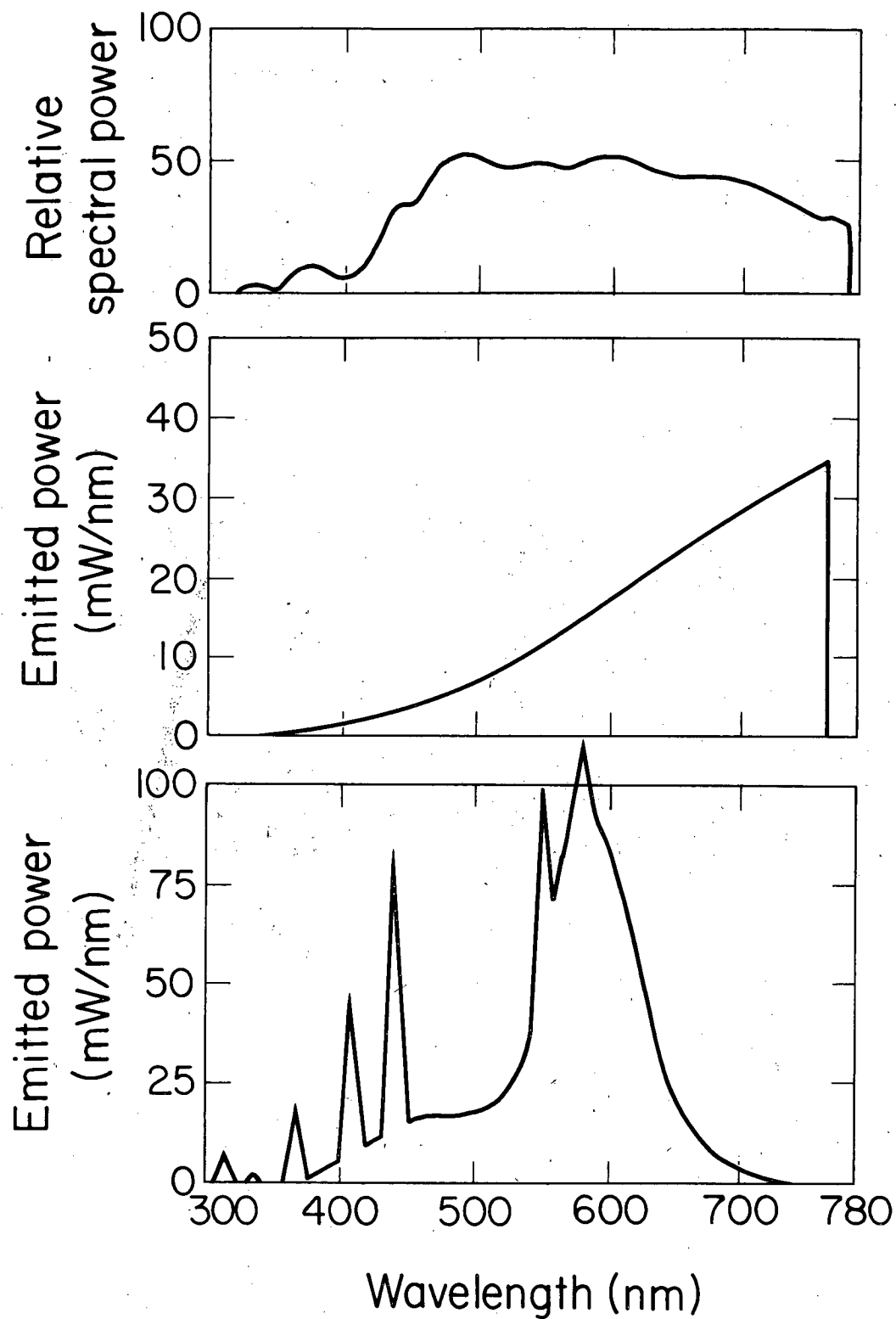
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Fig. 1. The ABC system of PSALI requires three switching groups: A for nighttime hours, B for daytime and nighttime hours, and C for increasing illuminance levels at the back of the room during bright daytime hours.



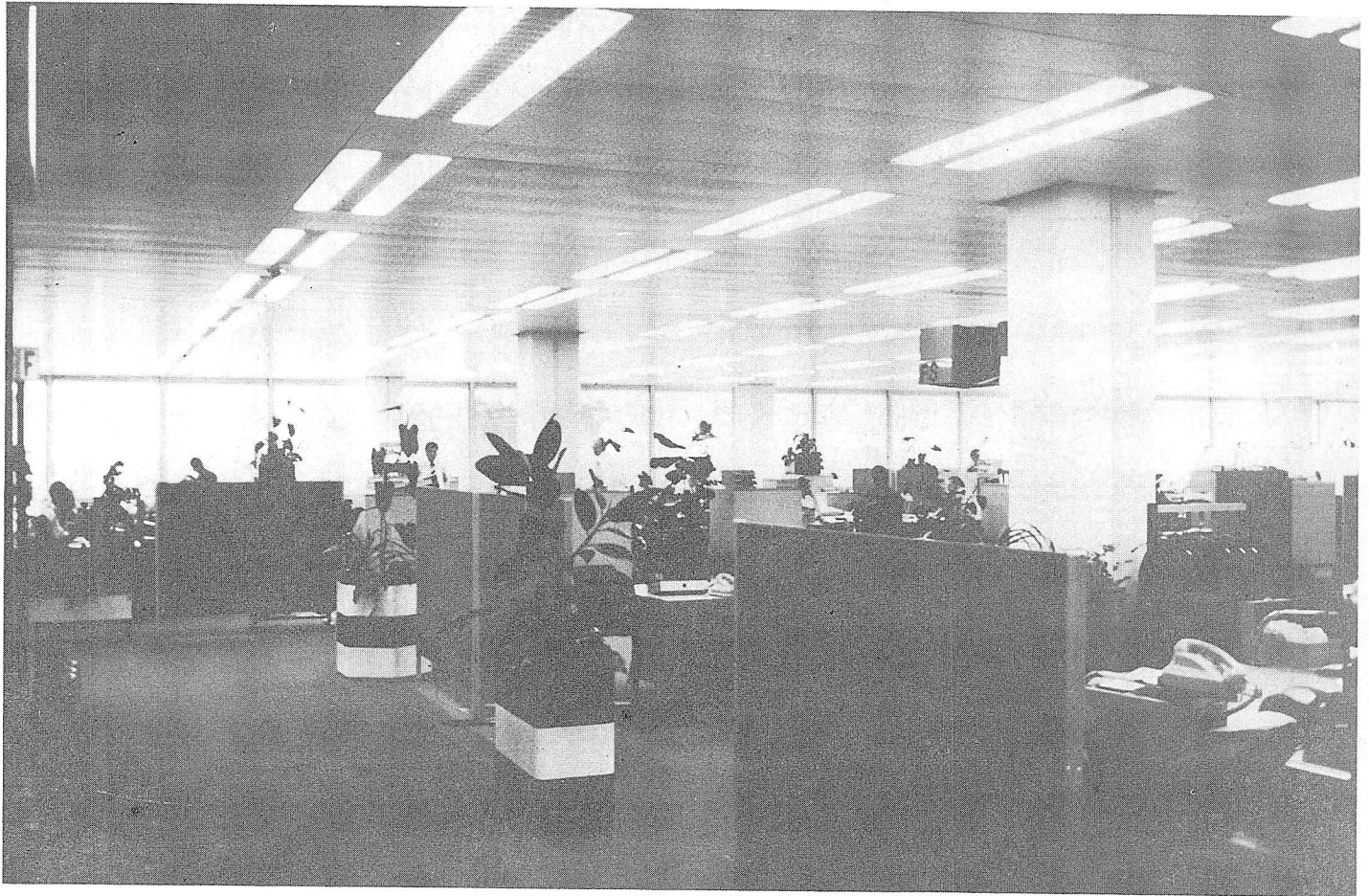
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Fig. 2. Study of critical minimum acceptable window size [Ref.8].



XBL 833-1397

Fig. 3. Spectral power distribution of (top) noon sunlight; (middle) incandescent lamp (1000 lm, GLS); and (bottom) white fluorescent lamp.



CBB 833-2021

Fig. 4. Typical open-space office with daylight dominant along the perimeter. Automatically operated louvers protect against direct sunlight and sky glare.

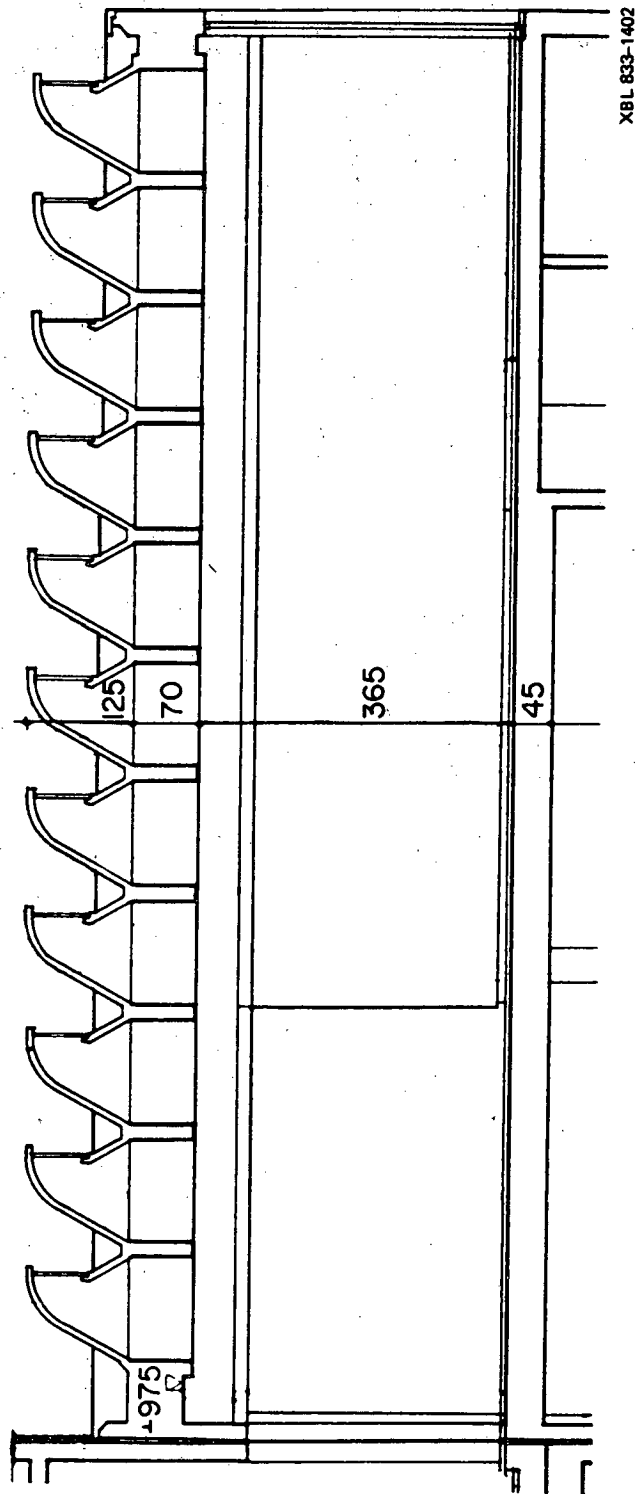
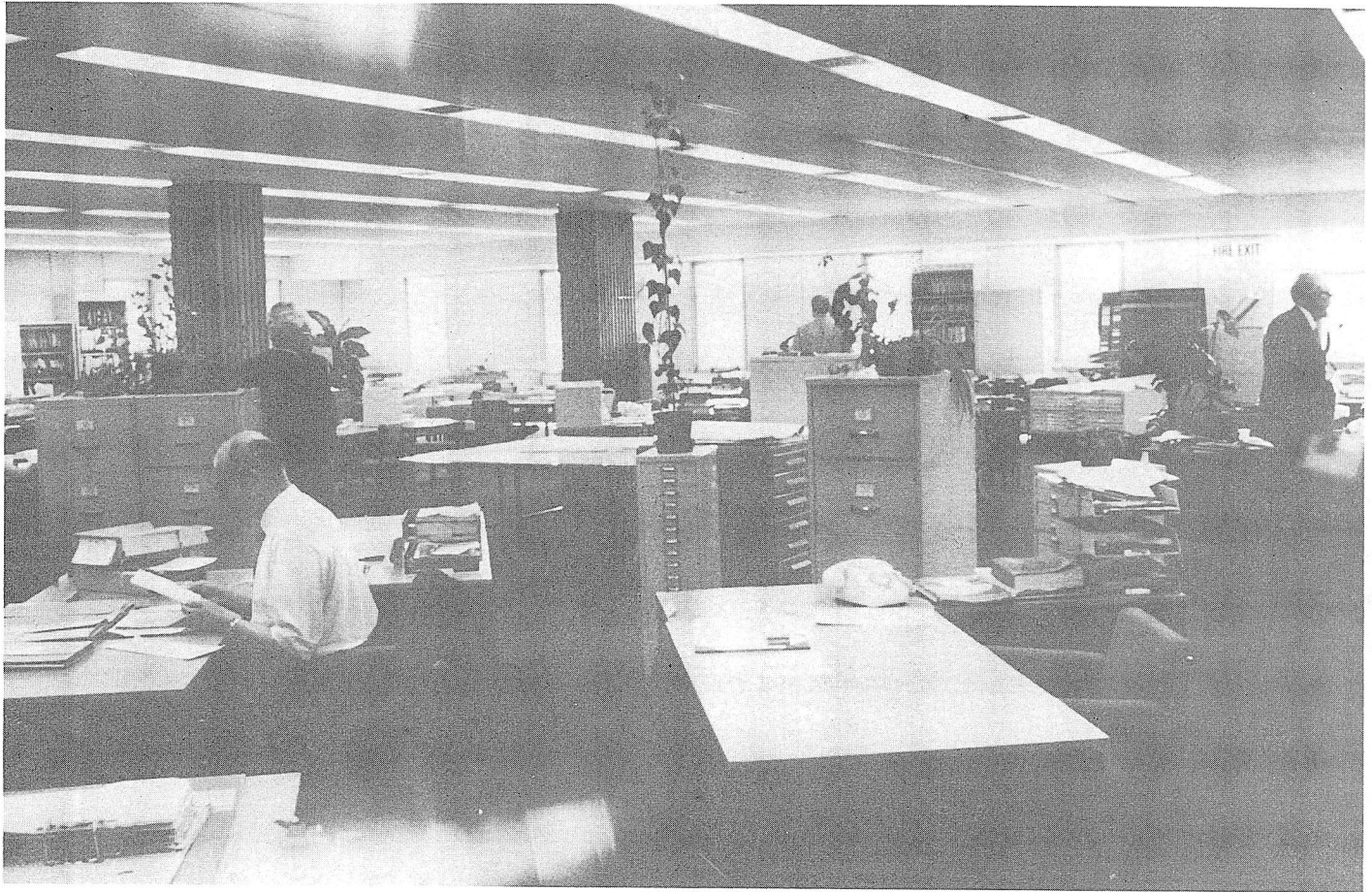


Fig. 5. Typical design of rooflights (skylights) with daylight dominant.



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Fig. 6. Typical open-space office with electric light dominant.  
Note the much smaller windows compared with those in the  
office shown in Fig. 4.

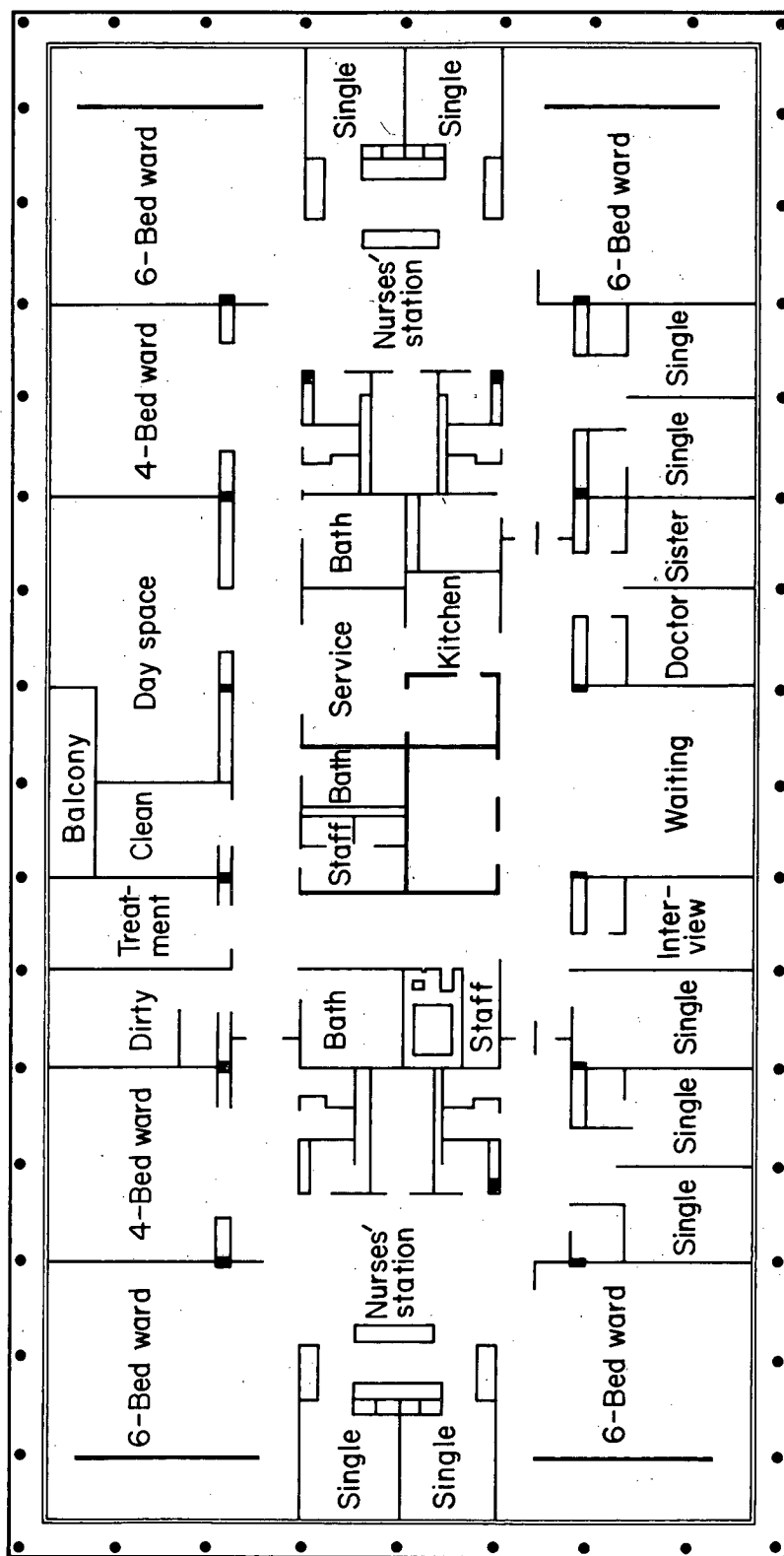
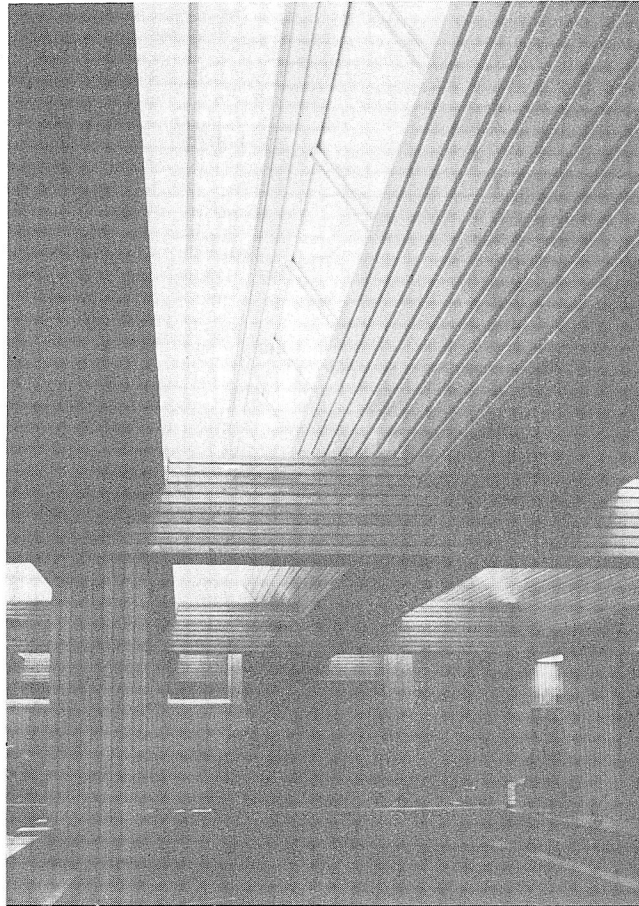
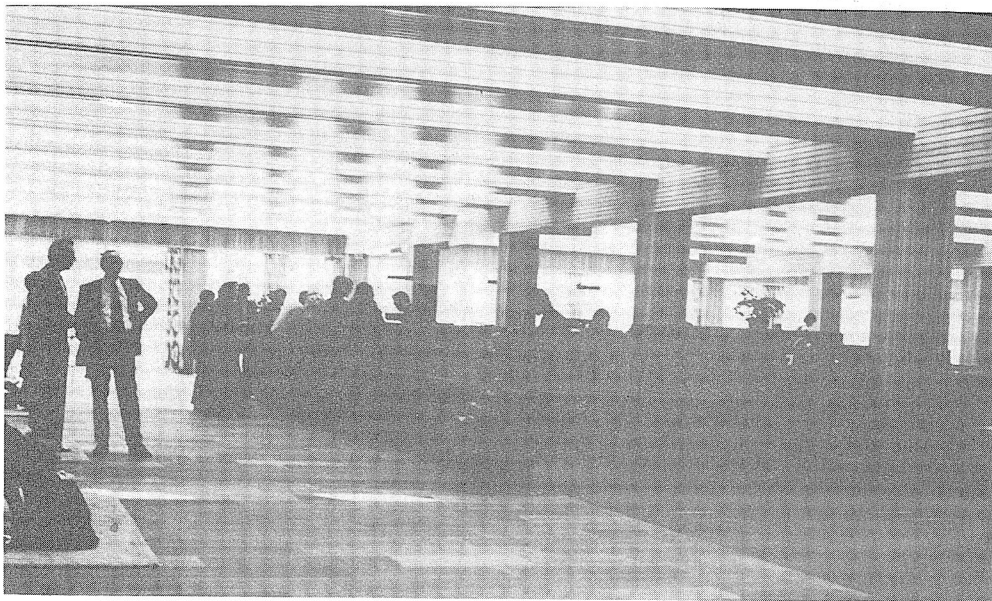


Fig. 7. Typical design of a deep-plan hospital floor with daylight dominant in peripheral patient rooms and electric light in the windowless inner rooms.





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Fig. 8. Dynamic automatic control of electric light levels according to availability of daylight on working surface.



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